

Abundance analysis of the slow nova PW Vulpeculae 1984

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ABSTRACT

We determine the elemental abundances for the ejecta of the slow nova PW Vul 1984. Our technique uses a minimization of the emission line fits of a photoionization model to available ultraviolet, optical and infrared spectra. We find the following abundances (by number) with respect to solar: $\text{He}/\text{H} = 1.0 \pm 0.4$, $\text{C}/\text{H} = 7.0^{+7}_{-4}$, $\text{N}/\text{H} = 85^{+59}_{-41}$ and $\text{O}/\text{H} = 6^{+7}_{-2}$. In addition, there is weak evidence for solar Ne and Mg and twice solar Fe. Previous studies (Saizar et al. 1991 and Andreä et al. 1991, 1994) of PW Vul have yielded considerable differences in their derived elemental abundances for the ejecta. Our abundances fall in between the previous studies. To explain the discrepant abundances, we analyze in detail the data and methods used to obtain the previous results. The abundances of Saizar et al. (1991) are significantly smaller than our values because of the lower electron temperature used by Saizar et al. in deriving elemental abundances from ion abundances. Andreä et al. (1991) used an ionization correction method to obtain their abundances and verified their results with a photoionization model (Andreä et al. 1994). Our analysis of their data shows that the absolute fluxes of the optical emission lines used by Andreä are underestimated by 15% leading to a factor of 2 increase in their derived abundances. We also find the photoionization model used by Andreä et al. (1994) predicts 2 times more carbon than the photoionization code we used even when fitting the same data with similar model parameters.

Key words:

stars: abundances – stars: individual – stars: novae.

1 INTRODUCTION

The slow novae PW Vul 1984 was discovered on 27.7 July UT by Wakuda (Kosai 1984). It reached maximum light of 6.3 mag in the V band on 4.1 August 1984. The light curve showed strong oscillations of 1-2 magnitudes on the decline (Robb and Scarfe 1995) making a determination of $t_{2,3}$ (the time to fall 2 or 3 magnitudes from maximum) uncertain. The light curve of PW Vul was similar to that of the proto-typical dust forming nova, DQ Her, however, infrared photometry of PW Vul did not indicate significant dust formation (Gehrz et al. 1988).

The early lightcurve showed strong oscillations making the distance determination from a standard rate-of-decline vs maximum magnitude relationship problematic. Gehrz et al. (1988) derived a distance of 6.5 kpc from the change in the blackbody angular radius of the photosphere *but assumed no interstellar extinction*. Evans et al. (1990) showed that assuming a realistic extinction of $E(B-V)=0.5$ increased the angular diameter and reduced Gehrz's distance to 3.3 kpc. Evans et al. (1990) assumed that PW Vul was emitting at the Eddington luminosity of a solar mass star at maximum light and that the absolute magnitude at maximum was the same as DQ Her to find 2.3 kpc and 2.6 kpc respectively assuming an $E(B-V) = 0.5$. Ringwald & Naylor (1996) obtained 1.6 ± 0.2 kpc from expansion parallax measurements in $\text{H}\alpha$ taken nine years after outburst. An average of the last four distance estimates gives 2.5 ± 1 kpc as our best estimate of the distance to PW Vul.

PW Vul has been observed in most wavelength regimes at various times during the outburst. Infrared spectra taken early in the outburst showed strong emission lines of neutral carbon, nitrogen and oxygen (Evans et al. 1990, Williams et al. 1996). Coronal lines of [S VI] ($1.96 \mu\text{m}$), [Mg VIII] ($3.02 \mu\text{m}$), [Al VI] ($3.65 \mu\text{m}$) and later Si VII ($2.47 \mu\text{m}$) and [Al V] ($2.90 \mu\text{m}$) slowly replaced the CNO lines as the infrared spectrum evolved (Williams et al. 1996). Optical spectra taken during the nebular phase showed strong emission lines of [O III] (5007, 4959 Å), [N II] (5755 Å) and Balmer hydrogen (Kenyon & Wade [1986; hereafter KW], Andreã et al. [1991 and 1994; hereafter A91 and A94], Saizar et al. [1991; hereafter S91]). The International Ultraviolet Explorer (IUE) satellite obtained spectra of PW Vul from the earliest phases of the outburst to well into the nebular phase when the ejecta had become optically thin. The X-ray satellite, EXOSAT, observed an increase in the X-ray flux over the first year of the outburst (Ögelman et al. 1987).

S91 and A91 determined elemental abundances from nebular spectra. S91 and A91 both utilized UV and optical spectra to determine *ionic* abundances of individual ions but differed in how they computed the *elemental* abundances. As a result, S91 found a factor of 4.1, 8.5, and 33.3 times *less* nitrogen, oxygen, and carbon, respectively, than A91. This is an important discrepancy and one that could easily call the determination of all nova abundances into question. For this reason, in this paper, we re-examine the available data and determine new elemental abundances for PW Vul. We use contemporaneous UV, optical, and infrared spectra in our modeling and use statistically robust minimization techniques to determine the photoionization model which predicts the best fit to the data. In addition, we critically examine the methods used by A91, A94 and S91 and suggest an explanation for the differences in their abundances.

2 DATA CALIBRATION AND REDDENING

In order to accurately model the abundances of nova ejecta, the spectra must be contemporaneous, flux calibrated and dereddened. We used ultraviolet, optical and infrared spectra obtained within a 2 week period during July 1985 because this is the largest amount of data available with the smallest time spread. We are justified in using data over this time span because the spectral development of PW Vul was slow enough so that even though the line fluxes changed, the *line flux ratios* were essentially the same during the months of June and July 1985. The ultraviolet was represented by the IUE spectrum SWP26342 taken on 3.09 July 1985. Unfortunately, there are no LWP observations on the same day but we used IUE spectrum LWP6264 (obtained on 24.6 June 1985) and spectrum LWP6408 (obtained on 16.7 July 1985) to estimate a Mg II (2800 Å) line strength for 3.09 July. A Gaussian fit was used to determine the integrated UV emission line fluxes. The primary source of uncertainty was in the determination of the continuum level and multiple Gaussian fits of each UV emission line provided an estimate of this uncertainty. An additional 10% was included in the uncertainty to account for the accuracy of the absolute flux determination of IUE (Bohlin 1980).

We used A91's spectra obtained during 1-6 July 1985 for the optical range. To assess the quality of A91's spectra, we compared them with the optical spectra published by KW from 2 June 1985 (their Table 1) and S91's 25 September 1985 (their Table 3) spectrum. The ratios of the strongest optical lines to H β in A91 were consistent with similar ratios in KW and S91. A91 places each emission line in an error class of 10-20%, 20-50% or greater than 50%. Lacking any more information about the error classes of A91, we set the uncertainty of each optical emission line to the average value of its assigned error class. In addition, we included the infrared Paschen lines Pa γ and Pa β and He I ($1.083 \mu\text{m}$) taken on 21 June 1985 (Williams et al. 1996). Williams et al. estimate uncertainties of 10% for Pa β and He I $1.08 \mu\text{m}$ and 20% for Pa γ . Table 1 contains the H β corrected line fluxes and their associated errors for the ultraviolet, optical and infrared spectra which we used.

The flux calibration of the data is critical since we are comparing optical, ultraviolet and infrared line fluxes. The IUE absolute fluxes have an error of about 10% but the absolute fluxes of the optical and infrared spectra were not as certain and depend on the photometric conditions under which the data were obtained. S91 showed that the absolute H β line flux, $f(\text{H}\beta)$, can be fit by the equation

$$\log(f(\text{H}\beta)) = -1.67 - 3.84\log(t), \quad (1)$$

where t is the number of days after S91's outburst date of 29 July 1984 (JD 2,445,911). Figure 1 shows the S91 (squares) and KW (triangles) absolute H β line fluxes as a function of time and the least-squares fit to these fluxes. A91 reported $f(\text{H}\beta) = 3.5 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ on 4 July 1985 ($t = 341$). This value is *about 15% smaller* than that obtained from equation 1 for day 341. A91's H β line flux is shown as a diamond in Figure 1. For our analysis, we used the absolute H β flux obtained from equation 1 for the date we chose to analyze. The IUE spectrum ($t=340$), A91's optical spectra ($t=341$), the infrared lines ($t=327$) and the Mg II lines ($t=330$ and $t=352$) are scaled, using equation 1, to the absolute H β flux on their respective dates of observation.

The reddening to PW Vul has been obtained by various methods. S91 estimated $E(\text{B-V}) = 0.6 \pm 0.06$ from the average ratio of the He II 1640 Å/4686 Å lines up to 2 years after outburst. A91 found that using $E(\text{B-V}) = 0.55 \pm 0.10$ removed the broad interstellar absorption feature at 2175 Å from IUE spectra. Williams et al. (1996) compared their Pa β and Pa γ line strengths of 20 March 1985 with KW's line strengths of H β and H γ on the same day. They found $A_V = 1.78 \pm 0.05$,

in excellent agreement with the other reddening values. In our analysis, we assumed an $E(B-V) = 0.55 \pm 0.05$ and used the extinction curve of Savage and Mathis (1979).

3 OPTIMIZATION OF PHOTOIONIZATION MODEL FITS

We used the photoionization code CLOUDY 90.02 (Ferland 1996) to predict the emission line fluxes relative to $H\beta$. CLOUDY simultaneously solves the equations of statistical and thermal equilibrium, incorporates collisional effects, and self-consistently treats energy balance and ionization.

CLOUDY requires numerous input parameters including the luminosity and the shape of the continuum of the central source, the inner and outer shell radius, the hydrogen density, the filling factor, and elemental abundances. In addition, CLOUDY allows the hydrogen density, $n(r)$, and filling factor, $f(r)$, to vary with the radius as,

$$n(r) = n(r_o)(r/r_o)^\alpha \text{ cm}^{-3} \text{ and} \quad (2)$$

$$f(r) = f(r_o)(r/r_o)^\beta, \quad (3)$$

where r_o is the inner radius, and α and β are the exponents of the power law.

Recently, powerful optimization techniques have been used to search multi-dimensional parameter space to find the best agreement between the predicted and observed line fluxes. Austin et al. (1996) used a Metropolis algorithm to determine the abundances of V1974 Cyg 1992 and QU Vul 1984. Vanlandingham et al. (1996) and Schwarz et al. (1997) applied a gradient mapping algorithm from a minimization routine, MINUIT (James and Roos, 1993), to V838 Her 1991 and LMC 1991, respectively. The MINUIT routine uses a Davidson-Fletcher-Powell (DFP) variable metric algorithm to search for a minimum in parameter space (see Press et al. 1992 for details).

For the abundance determinations of PW Vul, we used MINUIT as a driver for CLOUDY. Following an initial guess of the input parameters, CLOUDY calculated the ratios of the emission line fluxes, M_i , to $H\beta$. The goodness of fit was estimated from the χ^2 of the model:

$$\chi^2 = \sum_i \frac{(M_i - O_i)^2}{(\sigma_i)^2}, \quad (4)$$

where O_i is the observed line flux ratio to $H\beta$ and σ_i is the error associated with the observed line. The number of degrees of freedom in the model, ν , is equal to the number of lines modeled minus the number of parameters used in the model. A good model has a $\chi^2 \approx \nu$.

In Figure 2 we show the lowest χ^2 fit determined by MINUIT to the early July observations and the relative contribution of each line to the overall χ^2 . The model had 14 parameters, $\nu = 12$ and a χ^2 of 12. The best-fitting model had a blackbody continuum with an effective temperature for the central source of 2.4×10^5 K. The progression from the early, cool ($\approx 1-2 \times 10^4$ K), optically thick atmosphere (Schwarz et al. 1997) to an optically thin, nebular shell illuminated by a hot source is consistent with the rise in X-rays seen by EXOSAT from 100 to 300 days after outburst (Ögelman et al. 1987). The luminosity was 6.3×10^{37} ergs s^{-1} , which is below the Eddington luminosity for a one solar mass white dwarf. The hydrogen number density of the best model was $1.1 \times 10^7 \text{ cm}^{-3}$ at the inner radius and decreased as a power law with an exponent of $\alpha = -0.3$.

S91 obtained expansion velocities of 600 km s^{-1} from the width of $H\beta$, consistent with KW's FWHM measurements of $H\alpha$, and 400 km s^{-1} from double peaks observed in [O III] (5007 Å) in nebular spectra obtained one to two years after outburst. Ringwald & Naylor (1996) measured an $H\alpha$ expansion velocity of about 500 km s^{-1} seven years after outburst. Observations taken very early in the outburst (Andrillat 1984, Rosino et al. 1984) found emission line widths consistent with expansion velocities of ≈ 1200 km s^{-1} . The inner radius of our model, 1.8×10^{15} cm (equal to a constant expansion velocity of 610 km s^{-1} for 340 days), was consistent with the lower expansion velocities reported. The outer radius was determined to be 7.6×10^{15} cm.

Recent HST images of V1974 Cyg 1992 (Paresce et al. 1995) and high resolution spectra of other novae indicate that the ejecta have a clumpy structure (Shore et al. 1993). Our analysis predicted a low filling factor that varies with radius, consistent with the structure seen in the emission lines. The filling factor of the best model was 0.025 at the inner radius and decreased as a power law with an exponent of $\beta = -0.6$. The hydrogen mass contained in this model shell was calculated from,

$$M_{shell} = n(r_o) f(r_o) \int_{R_{inner}}^{R_{outer}} (r/r_o)^{\alpha+\beta} dV(r), \quad (5)$$

where $V(r)$ is the volume of the model. Using the model parameters, a hydrogen shell mass of $1.6 \times 10^{-4} M_\odot$ was determined with a range of uncertainty between 3×10^{-3} and $3 \times 10^{-6} M_\odot$. Our derived ejected mass was 3 times the value that Stickland et al. (1981) derived for the fast CO nova V1668 Cyg 1978. This high an ejected mass is consistent with the slow speed class of PW Vul. Slow novae are believed to occur on less massive white dwarfs than fast novae and can, therefore, accrete more mass before the explosion.

The helium, carbon, nitrogen, and oxygen abundances all showed enhanced values relative to solar with nitrogen being the highest at 85 times solar. The magnesium and iron abundances were found to be one and two times the solar values, respectively. These abundances are estimates only since the MgII 2800 Å doublet and the [Fe VII] 6087 Å line are the only features of those species used in the analysis and [Fe VII] 6087 Å is quite weak. No neon lines are reported by A91 but a solar neon abundance predicted a Ne III (3869 and 3967 Å) line flux that was consistent with earlier values reported by KW on 2 June 1985. In Figure 3, we compare our derived abundances with those of S91 and A94.

In Table 2, we present the parameters and uncertainties from our lowest χ^2 model for early July. To estimate the uncertainty in the parameters, the model was recomputed, increasing or decreasing one parameter at a time. The amount by which the parameter could be changed and still provide an acceptable χ^2 corresponds to the uncertainty. $\chi^2 \approx 23$ was deemed the lowest χ^2 that a model could have and still provide an acceptable fit to the data.

We then increased $E(B-V)$ to 0.60, in order to estimate how the uncertainty in the reddening affected the derived abundances. The larger reddening mainly affects the higher ionization lines in the ultraviolet. The best model now required a combination of about twice the carbon, nitrogen, oxygen and magnesium abundances as before, a lower luminosity, (2.2×10^{37} ergs s $^{-1}$), and smaller inner and outer radii (1.4 and 4×10^{15} cm). The increase in the abundances increased all line ratios so as to fit the higher reddening but overestimated the strongest lines in the ultraviolet. The decrease in the luminosity compensated for this effect by decreasing the high ionization emission line strengths relative to the low ionization lines.

As a check of our abundance solution, we modeled KW's optical spectrum of 25 April 1986 and the IUE spectra SWP28068 and LWP7925 on 31 March 1986. The line fluxes were scaled to the absolute H β flux on their respective dates with equation 1. Since only line fluxes of H β and the strong [O III] lines (4363, 4959 & 5007 Å) were reported by KW, the total number of line flux ratios available to be modeled was only 13. The model had an equal number of parameters and data points making it impossible to obtain a statistically reasonable fit for this date. However, we can use the best fit model as a confirmation of our previous solution. As a starting point for MINUIT, we used the same luminosity, blackbody temperature and inner filling factor used for July 1985. We assumed a lower constant hydrogen density ($\alpha = 0$) and an initial inner radius consistent with a constant expansion velocity of 610 km s $^{-1}$ over 670 days. The best fit ($\chi^2=4$) was found with an effective temperature of 2.2×10^5 K, a constant hydrogen density of 10^6 cm $^{-3}$, a constant filling factor of 0.016 and an inner radius of 4×10^{15} cm. The outer radius was 3.2×10^{16} cm. The ejected mass of this model, 2×10^{-3} M $_{\odot}$, is over a factor of 10 higher than before and confirms the high ejected mass derived in July 1985. Our fit indicated that the luminosity and blackbody temperature did not change much in the ten months between the dates modeled. The abundances of helium, carbon, nitrogen, oxygen and magnesium were 1, 5, 72, 6.8, and 0.8 times solar abundances, respectively. These abundances are well within the errors of previously calculated abundances for July 1985 and support our abundance determinations for PW Vul.

4 ABUNDANCE DETERMINATIONS OF SAIZAR ET AL. (1991)

To derive the elemental abundances of helium, nitrogen, and oxygen. S91 used 4 to 6 optical spectra taken from early 1985 until mid 1987. The carbon abundance was determined using two ultraviolet spectra that were contemporaneous with optical spectra. The final elemental abundances were averages of all the observations in which the elements were observed.

S91 obtained the helium to hydrogen abundance from:

$$\frac{He}{H} \approx \frac{HeII}{HII} + \frac{HeIII}{HII}. \quad (6)$$

The ion abundances were given by:

$$\frac{HeII}{HII} = \frac{j(HeI)}{j(H\beta)} \frac{\alpha_{H\beta}}{\alpha_{HeI}} \frac{5876}{4861} \quad (7)$$

$$\frac{HeIII}{HII} = \frac{j(HeII)}{j(H\beta)} \frac{\alpha_{H\beta}}{\alpha_{HeII}} \frac{4686}{4861} \quad (8)$$

where α is the recombination coefficient and $j/j(H\beta)$ is the line ratio to H β . S91 accounted for collisional excitation from the metastable 2s 3S level of He I by using the correction of Clegg (1987). The HeII/HII ratio was multiplied by $(1+C/R)^{-1}$ where C/R is the ratio of excitations by collisions to recombinations and is tabulated by Clegg.

To derive the metal abundances, S91 assumed that the ratio of elemental abundances was approximately the same as the ratio of ion abundances for elements with similar ionization potentials. S91 used the following approximations to determine the elemental ratios from optical spectra:

$$\frac{O}{H} \approx \frac{OIII}{HeII} \left(\frac{HeII + HeIII}{HII} \right) = \frac{OIII}{HII} \left(1 + \frac{HeIII}{HII} \frac{HII}{HeII} \right) \quad (9)$$

$$\frac{N}{H} \approx \frac{NII}{OII} \left(\frac{OII + OIII}{HII} \right) = \frac{NII}{HII} \left(1 + \frac{OIII}{HII} \frac{HII}{OII} \right) \quad (10)$$

The ion abundances relative to hydrogen are given by:

$$\frac{OIII}{HII} = \frac{j(\lambda\lambda 4959 + 5007)}{j(H\beta)} \frac{5007}{4861} \left(\frac{N_e \alpha_{H\beta}}{A_{1D_2-3P} N_{1D_2}} \right) \quad (11)$$

$$\frac{NII}{HII} = \frac{j(\lambda 5755)}{j(H\beta)} \frac{5755}{4861} \left(\frac{N_e \alpha_{H\beta}}{A_{1S_0-1D_2} N_{1S_0}} \right) \quad (12)$$

$$\frac{OII}{HII} = \frac{j(\lambda\lambda 7320 + 7330)}{j(H\beta)} \frac{7325}{4861} \left(\frac{N_e \alpha_{H\beta}}{N_{2P_{1/2}}(A_{2P_{1/2}-2D_{3/2}} + A_{2P_{1/2}-2D_{5/2}}) + N_{2P_{3/2}}(A_{2P_{3/2}-2D_{3/2}} + A_{2P_{3/2}-2D_{5/2}})} \right) \quad (13)$$

where N_e is the electron number density, A is the transition probability, and N is the relative fraction of ions in the given level. Using the ultraviolet spectra, the carbon to oxygen abundance was found from,

$$\frac{C}{O} \approx \frac{CIII}{OIII} = \frac{j(\lambda\lambda 1907 + 1909)}{j(\lambda\lambda 1663 + 1666)} \frac{1908}{1665} \left(\frac{A_{5S-3P} N_{5S}(OIII)}{A_{3P-1S} N_{3P}(CIII)} \right). \quad (14)$$

Since S91 never used the ratio of ultraviolet to optical lines, their analysis was not affected by errors in the absolute flux calibration of the optical spectra. The uncertainty in the reddening was also less important since the abundances were determined from line ratios of similar wavelengths. In addition, S91's analysis had the advantage of multiple observations over two years.

From the [O III] line ratios $j(\lambda\lambda 1660 + 1666)/j(\lambda\lambda 4959 + 5007)$ and $j(\lambda 4363)/j(\lambda\lambda 4959 + 5007)$, S91 determined the electron temperatures and densities for the four dates that both optical and ultraviolet spectra existed. S91 found a constant electron temperature of 13,200 K and an electron density decreasing from $7.6 \times 10^6 \text{ cm}^{-3}$ on day 253 to $1.7 \times 10^5 \text{ cm}^{-3}$ on day 681.

The derived electron temperature and density were assumed to be constant throughout the shell for each date. This assumption gives at best only a rough abundance solution since higher ionization ions are expected to form in higher temperature and denser regions than the low ionization ions. This can be seen in Figure 4 where the electron density, electron temperature, and relative ion concentrations of our best July model are presented as a function of radius. To determine the effect of using more realistic electron temperatures and densities for each different region of the shell on the final elemental abundances, we used the average electron temperature and density (from the region where the ion was dominant in our best July model) to obtain the ion abundances relative to ionized hydrogen in equations 6-14. The average electron temperatures and densities of the various ion regions are given in Table 3. We used the line ratios reported in S91 and the atomic constants of Mendoza (1983). The relative level populations were calculated with a three level atom for [O III] and [N II], a five level atom for [O II], and a simple two level atom for the C III]/[O III] calculation. In Table 4, we compare the elemental abundances of S91 with the abundances derived from our model averaged electron temperatures and densities. The model averaged electron temperatures and densities are more realistic and, in conjunction with S91's measured line fluxes, give higher abundances that are much closer to the abundances of our best fitting July photoionization model. The primary reason for the increase seen in these abundances is the generally lower electron temperatures. The lower electron temperatures produce fewer ions in excited levels and thus the total ion abundances must be increased to produce the same observed emission line strengths.

5 ABUNDANCE DETERMINATIONS OF ANDREÄ ET AL. (1991,1994)

When modeling combined ultraviolet and optical spectra, an accurate flux calibration is needed between the spectral regions. To see why, consider that during the nebular phase the ultraviolet contains strong emission lines of high ionization potential (N V 1240 Å, N IV] 1486 Å, N III] 1750 Å, C IV 1550 Å, C III] 1909 Å, O IV] 1401 Å, and O III] 1666 Å) while the optical contains strong emission lines from species with a lower ionization potential ([N II] 5755 Å, [O III] 4959, 5007 Å, [O II] 7325 Å, and [O I] 6300, 6363 Å). If the absolute optical calibration is underestimated so that the optical fluxes are too low, then the ratio of ultraviolet/optical lines will be too large and the ionic abundances of the lower ionization potential ions will be too low. An analysis of the line fluxes will lead to preferentially populated higher ion stages. This creates the false impression that a substantial fraction of the elements are in higher (unobserved) ionization stages, leading to over estimates of the elemental abundances.

As stated in §2, A91 obtained an H β flux that was about 15% smaller than that given by equation 1. We will address how this affected the abundance analysis later in this section but for now we use only the line fluxes as measured by A91. Adopting the values of A91 allow us to directly compare the abundances determined by A91 and A94 with our best fits to their data using our techniques.

A91 applied ionization correction factors (ICFs) to estimate the fraction of an element in unobserved ionization stages. This method assumes that an ICF derived for one element holds for *all* other elements and is also dependent on the number

of the ionization stages observed. A91 used simultaneous optical and UV spectral observations to obtain as many elemental ionization stages as possible.

The ICF for each element was determined by A91 from:

$$ICF = \frac{C}{(I_2 - I_1)} \quad (15)$$

where C is a constant and I_2 and I_1 are the ionization potentials of the highest and lowest ion observed, respectively. A91 estimated that 95% ($ICF = 1.05$) of the nitrogen was observed in the ionization stages N II to N VI giving $C = 87.6$ eV. This constant, derived solely from the nitrogen ion abundances, was used in equation 18 to determine the ICF for all other elements.

As a check of the accuracy of A91's ICFs, we used the same parameters and abundances used by A94 (A94's photoionization model #1) in CLOUDY to obtain the volume averaged ionization fractions. *We note that we are only comparing the ICFs determined by A91 and not the methods by which the ion abundances were derived.* In Table 5, we present the ion abundances as a fraction of the elemental abundance for the first six ionization stages. The last column gives the ICFs determined for unobserved ions. The more detailed ionization calculations of CLOUDY predict more neutral nitrogen and oxygen and less N IV and O VI than A91 but the ICFs are in close agreement with those determined by A91. The agreement in ICFs is not surprising, since A91 observed both nitrogen and oxygen in five ionization states and estimated that they had accounted for a majority of the abundances of these elements. The differences between ICFs and photoionization modeling were more clearly shown in carbon, where only three ionization states were observed. The carbon ICF of A91 was significantly larger than the ICF of CLOUDY and thus would predict 1.4 times more carbon than CLOUDY. As expected, the ICF method provides poor abundance solutions when too few ionization stages of an element are available in the spectra.

The abundances derived by A91 were checked in A94 by comparing with the results from a photoionization model. A94 reported that their best fit model had slightly higher abundances of nitrogen, oxygen and iron and 20% less carbon than found by A91 from the ICF method. We assumed this to mean a 5% increase in nitrogen, oxygen and iron from their ICF method abundances. The difference in carbon abundance between the two methods again reflects an inaccuracy in the ICF method when insufficient ionization stages are observed.

We then used A94's best photoionization model parameters (their model #2) in CLOUDY to check the consistency of the two codes. In Table 6 we present the emission line strengths predicted by CLOUDY and A94, A94's measured emission line strengths, and the average line errors given by A91. The biggest difference is seen in the predictions of C IV 1550 Å and C III] 1909 Å. All other lines are within 20-30% of one another.

Clearly there are differences between the two photoionization codes. To determine if the differences are significant, MINUIT optimized the A94 parameters with respect to the measured line fluxes to find the best fit parameters. Ideally, the minimized parameters should not be too different from their best model. The parameters given by A94 were used as the starting points for MINUIT. We did this twice, first with the filling factor and the radial dependence of the density and filling factor allowed to vary. The second had the filling factor set equal to 1 and the radial dependence of the density and filling factor set to zero to duplicate the assumptions of A94. The results are given in Table 7 along with the χ^2 of the two models. The physical parameters for both minimized models were close to those of A94. When the filling factor was not fixed, MINUIT found the lowest χ^2 for a low constant filling factor of 0.045, consistent with the observations and our results. The CNO abundances from the low filling factor model were greater than those obtained in the fixed filling factor model.

In our models, we generally find that if the filling factor is decreased, then the luminosity, density and abundances have to be increased (with all other parameters roughly the same) in order to fit the same measured line fluxes. A decrease in the filling factor causes higher predicted line fluxes in [O I] (6300, 6363 Å), [O II] (7320, 7330 Å) and [N II] (6548, 6584 Å). In the lower filling factor model, these lines form in a region with a larger electron density than the same lines in the high filling factor model. The decrease in the filling factor allows the more energetic photons to penetrate further into the shell and the electron density increases as a result of the increased ionization. This leads to an increase in the number of collisional excitations and, in turn, to the increased line emission observed. The situation can be somewhat alleviated by increasing the luminosity and density but the best model requires slightly higher abundances to match the measured line fluxes.

The fixed filling factor model used all the parameters included in A94's model and thus is the model to compare to A94's model for a predictive test of the photoionization codes. The abundances were within 30% of A94's values except for carbon. The carbon abundance is less than half that found by A94, indicating a factor of ≥ 2 disagreement between the models. Even the best fit model with a more realistic filling factor did not provide enough carbon to reproduce A94's value. A detailed study of the reasons for the carbon differences is beyond the scope of this paper. We conclude that the choice of the photoionization code was responsible for the major contribution to the differences in the carbon abundance.

To estimate the effect of a difference in the flux calibration on the abundances, we found the best fit to our July 1985 data using the $H\beta$ flux given by A91 instead of equation 1. The primary result of not including this correction was higher ultraviolet line fluxes relative to $H\beta$, resulting in higher carbon, nitrogen, oxygen and magnesium abundances. We started our minimization process with the same parameters as in our $H\beta$ flux corrected model but with higher CNO abundances. The

best fit model had roughly the same physical parameters except it is 1/3 as luminous and has 1/3 the inner radius as the flux corrected model. In addition, the best fit model had 1.5, 1.6 and 2 times more C, N and O elements than the flux corrected model.

6 CONCLUSION

We have determined our own set of elemental abundances for the slow nova PW Vul 1984 from the largest set of available contemporaneous UV, optical and infrared spectra. The abundances were found using a photoionization code, combined with a minimization technique to search parameter space for the best agreement between the predicted and observed emission line fluxes. From our lowest χ^2 model, we found that helium, carbon, nitrogen, and oxygen showed enhancements of 1.0 ± 0.4 , 7.0^{+7}_{-4} , 85^{+59}_{-41} and 6^{+7}_{-2} times the solar value, respectively. In addition, we found weak evidence (modeling only 1 weak line each) that neon and magnesium had solar abundances while Fe had twice the solar abundance. The expansion velocity derived from the inner radius, $\approx 600 \text{ km s}^{-1}$, and the blackbody effective temperature, $2.4^{+0.27}_{-0.4} \times 10^5 \text{ K}$ of our photoionization model are consistent with X-ray and high resolution optical spectra. The low value of the filling factor is consistent with both the observed line profiles and the clumpiness seen in HST images of the ejecta of nova V1974 Cygni 1992 and other novae. We determined that our uncertainty in the reddening equated to a factor of 2 in the abundances. We applied the same techniques to optical and UV spectra obtained 10 months after our best fit as a predictive test of our elemental abundances and parameters. The blackbody temperature and luminosity were approximately the same and the radii were consistent with the expansion determined from the previous best fit model. The hydrogen density and filling factor decreased and all of the abundances were well within the error range established in the first model, confirming our abundance solution.

Theoretical modeling predicts that the nova outburst occurs as the result of thermonuclear runaways in the accreted hydrogen rich envelopes of white dwarfs (Starrfield 1989). The abundance analyses of nova ejecta show, for most novae, that there has been significant mixing of the accreted material with core material which has either a CO or an ONeMg composition (Starrfield et al. 1997). This enrichment appears as large overabundances of a variety of elements from carbon through silicon depending on the particular nova. In the case of PW Vul, we find that the CNO elements comprise about 13% of the mass of the ejecta. In contrast, the CNO elements comprise 1.3% of solar material. The amount and distribution of the enrichments implies mixing with a CO white dwarf core. The abundances of Ne and Mg are solar which supports our contention that the core material does not contain enriched neon and magnesium. Finally, our model gives an ejected mass of $\sim 1.6 \times 10^{-4} M_{\odot}$ which suggests that the outburst took place on a white dwarf with a mass of $\sim 1.05 M_{\odot}$ (Starrfield 1989).

We studied the methods used by S91, A91 and A94 and were able to reproduce the abundances reported by these authors using their data and methods. S91 used a plasma diagnostic approach to obtain the average ion abundances from spectra obtained between 1 and 3 years after outburst (primarily optical). Ratios of ions with similar ionization potentials were assumed to be equal to their elemental abundance ratios. Applying these assumptions but using more realistic electron temperatures and densities gave higher abundances which were similar to those determined from our best photoionization model. We conclude that the abundances of S91 are significantly lower than ours because of the higher electron temperatures used by S91.

A91 used the ICF method to obtain their abundances. This technique assumed a correction to the elemental abundances caused by unobserved ionization states. Contemporaneous optical and ultraviolet spectra were used to maximize the number of observable ionization states of as many elements as possible. A94 then used a photoionization code to verify the results of A91's ICF method. We used the parameters and line flux measurements given by A94 in our photoionization code to assess the accuracy of the ICF method. For elements that had many observed ionization stages such as nitrogen and oxygen, we found that the ICF method is a good approximation but when fewer ionization stages were observed, such as for carbon, the approximation was poor. For example, the ICF method predicted 1.4 times more carbon than was present in our model and 20% more than in A94's model.

A consistency check between CLOUDY and the photoionization model used by A94 showed persistent differences in the carbon abundances. We optimized A94's best parameters to the measured emission line strengths of A91 to see how close the final best fit parameters compared with A94's values. All of our parameters were within 20-30% of A94 except for carbon which had only 1/2 of A94's abundances. These results imply that the two codes produce consistent results under these circumstances except for a factor of 2 in the derived carbon abundance.

The ICF and photoionization modeling of optical and ultraviolet data required that the spectra be absolutely flux calibrated. A91 found 15% less H β flux than calculated by S91 from observations of the decline of the H β flux over 2 years of observations. Modeling our data with the H β absolute flux of A91 produced carbon, nitrogen, oxygen, and magnesium abundances that were over 2 times greater than our best fit models with our value of H β . *This underscores the need for contemporaneous and absolute flux calibrated optical and UV spectral observations to accurately determine the elemental abundances.* A91's analysis consisted of simultaneous optical and UV spectra at only *one* epoch and thus their results depended on the value of the flux of H β . Increasing our best fit abundances by a factor of 2 (to roughly compensate for the H β flux used

by A91) and increasing the carbon abundance by another factor of 2 (to compensate for the differences in the photoionization codes) gave high elemental abundances roughly equal to those reported by A94.

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Table 1. Line fluxes relative to H β from equ. 1

| Element (\AA) | flux/flux(H β) | error (%) |
|--------------------------|-----------------------|-----------------|
| N v 1240 | 1.1 | 30 ^a |
| C II 1335 | 0.12 | 45 ^a |
| O IV] 1402 | 0.27 | 35 ^a |
| N IV] 1486 | 1.7 | 30 ^a |
| C IV 1550 | 2.6 | 30 ^a |
| He II 1640 | 0.29 | 35 ^a |
| O III] 1666 | 0.24 | 35 ^a |
| N IV 1718 | 0.06 | 65 ^a |
| N III] 1750 | 1.2 | 30 ^a |
| C III] 1909 | 1.4 | 30 ^a |
| Mg II 2800 | 0.42 | 40 ^b |
| H γ 4340 | 0.37 | 40 ^c |
| [O III] 4363 | 2.1 | 40 ^c |
| He II 4686 | 0.34 | 30 ^c |
| H β 4861 | 1.00 | 15 ^c |
| [O III] 4959 | 2.7 | 30 ^c |
| [O III] 5007 | 7.9 | 30 ^c |
| [N II] 5755 | 1.6 | 30 ^c |
| He I 5876 | 0.14 | 30 ^c |
| Fe V II] 6087 | 0.21 | 30 ^c |
| [O I] 6300 | 0.17 | 50 ^c |
| [O I] 6363 | 0.11 | 30 ^c |
| [N II] 6548 | 0.37 | 65 ^c |
| H α 6563 | 4.4 | 30 ^c |
| [N II] 6584 | 1.1 | 65 ^c |
| He I 10830 | 2.9 | 35 ^d |
| Pa γ 10938 | 0.19 | 45 ^d |
| Pa β 12818 | 0.47 | 35 ^d |

^a UV: SWP26342 on 3.09 July 1985.

^b UV: average of LWP6264 on 24.6 June 1985 and LWP6408 on 16.7 July 1985.

^c Optical: Andreä et al. (1991) on 1-6 July 1985.

^d Infrared: Williams et al. (1996) on 21 June 1985.

8 TABLES

Table 2. Parameters of best fitting model for June/July observations

| Parameter | Value |
|---------------------------------|---|
| Black body temperature | $2.4^{+0.27}_{-0.40} \times 10^5$ K |
| Source luminosity | $6.3^{+1.6}_{-3.3} \times 10^{37}$ ergs s ⁻¹ |
| Hydrogen density | $1.1^{+1.4}_{-0.1} \times 10^7$ cm ⁻³ |
| α^a | $-0.3^{+0.3}_{-0.13}$ |
| Inner radius | $1.8^{+1.9}_{-1.3} \times 10^{15}$ cm |
| Outer radius | 7.6×10^{15} cm ^b |
| Filling factor | $0.025^{+0.055}_{-0.013}$ |
| β^c | $-0.6^{+0.6}_{-0.9}$ |
| He/He _⊙ ^d | 1.0 ± 0.4 |
| C/C _⊙ ^d | 7.0^{+7}_{-4} |
| N/N _⊙ ^d | 85^{+59}_{-41} |
| O/O _⊙ ^d | 6^{+7}_{-2} |

^a Radial dependence of the density r^α .

^b Model is insensitive to an upper limit for the outer radius because it is radiation bounded.

^c Radial dependence of the filling factor r^β .

^d Log of the solar number abundances relative to hydrogen
He:-1.0 C: -3.45 N:-4.03 O: -3.13 (Grevesse & Noel 1993). Estimates
on the Ne, Mg and Fe abundances are -3.93, -4.42 and -4.2.

Table 3. Averaged electron temperatures and densities of best fit model

| Element | T_e (K) | N_e (cm^{-3}) |
|---------|-----------|----------------------------|
| He III | 15,000 | 1.3×10^7 |
| H II | 14,000 | 1.1×10^7 |
| He II | 11,000 | 8.5×10^6 |
| C III | 11,000 | 8.8×10^6 |
| O III | 11,000 | 8.8×10^6 |
| N II | 9,000 | 6.0×10^6 |
| O II | 9,000 | 6.0×10^6 |

Table 4. Abundance comparison to S91

| Element ^a | S91 | CLOUDY ^b |
|----------------------|-----|---------------------|
| He/He _⊙ | 0.9 | 1.0 |
| C/C _⊙ | 1.1 | 2.8 |
| N/N _⊙ | 55 | 139 |
| O/O _⊙ | 1.8 | 7.3 |

^a Log of the solar number abundances relative to hydrogen

He:-1.0 C: -3.45 N:-4.03 O: -3.13 (Grevesse & Noel 1993).

^b Abundances from our electron temperatures and densities in equ 12-16.

Table 5. Comparison of ICF derived by A91 and predicted by CLOUDY

| Element | Method | I | II | III | IV | V | VI | ICF |
|----------|--------|------|------|------|------|------|------|------|
| Carbon | A91 | nl | 0.18 | 0.32 | 0.10 | nl | nl | 1.65 |
| Carbon | CLDY | 0.0 | 0.31 | 0.41 | 0.10 | 0.18 | 0.00 | 1.22 |
| Nitrogen | A91 | 0.00 | 0.08 | 0.45 | 0.35 | 0.08 | nl | 1.05 |
| Nitrogen | CLDY | 0.22 | 0.10 | 0.41 | 0.14 | 0.08 | 0.06 | 1.04 |
| Oxygen | A91 | 0.02 | 0.16 | 0.29 | 0.41 | nl | nl | 1.10 |
| Oxygen | CLDY | 0.27 | 0.05 | 0.41 | 0.14 | 0.09 | 0.04 | 1.15 |

nl: line not observed in spectra.

Table 6. Comparison of CLOUDY and A94's photoionization model

| Element (\AA) | CLOUDY ^a | A94 model ^a | A94 measured ^{ab} |
|--------------------------|---------------------|------------------------|----------------------------|
| N v 1240 | 36.5 | 28.8 | $30.4 \pm 15\%$ |
| C II 1335 | 3.7 | 3.7 | $2.0 \pm 40\%$ |
| O IV] 1402 | 2.6 | 3.3 | $4.0 \pm 40\%$ |
| N IV] 1486 | 24.5 | 24.0 | $20.9 \pm 15\%$ |
| C IV 1550 | 46.9 | 27.3 | $30.0 \pm 15\%$ |
| He II 1640 | 2.7 | 2.1 | $2.4 \pm 40\%$ |
| O III] 1666 | 2.2 | 2.8 | $2.0 \pm 40\%$ |
| N IV 1718 | 1.1 | 0.85 | $0.65 \pm 75\%$ |
| N III] 1750 | 10.6 | 10.0 | $12.6 \pm 15\%$ |
| C III] 1909 | 21.1 | 14.9 | $18.3 \pm 15\%$ |
| [O II] 2471 | 0.19 | 0.34 | $0.83 \pm 75\%$ |
| Mg II 2800 | 0.42 | 0.55 | $1.80 \pm 75\%$ |
| H γ 4340 | 0.49 | 0.46 | $0.52 \pm 40\%$ |
| [O III] 4363 | 2.65 | 2.7 | $2.7 \pm 15\%$ |
| He II 4686 | 0.29 | 0.32 | $0.37 \pm 15\%$ |
| [O III] 4959 | 3.3 | 2.6 | $2.5 \pm 15\%$ |
| [O III] 5007 | 9.4 | 7.8 | $7.5 \pm 15\%$ |
| [N II] 5755 | 0.68 | 1.0 | $1.1 \pm 15\%$ |
| He I 5876 | 0.11 | 0.13 | $0.10 \pm 15\%$ |
| H α 6563 | 2.8 | 2.9 | $2.3 \pm 15\%$ |

^a Line fluxes relative to H β .^b Error estimates from A91.

Table 7. Parameters of best photoionization model fit to A91 line fluxes

| Parameter | CLDY+MIN ^{a,c} | CLDY+MIN ^{b,c} | A94 |
|---|-------------------------|-------------------------|------|
| BB temp ($\times 10^5$ K) | 2.3 | 2.3 | 2.5 |
| Lum ($\times 10^{38}$ ergs s ⁻¹) | 1.9 | 1.3 | 1.6 |
| H Den ($\times 10^7$ cm ⁻³) | 1.3 | 1.1 | 1 |
| Radius ($\times 10^{15}$ cm) | 4 | 4.4 | 4.3 |
| α | -0.1 | 0.0 | 0.0 |
| filling factor | 0.045 | 1.0 | 1.0 |
| β | 0.0 | 0.0 | 0.0 |
| He/He _⊙ ^d | 1.0 | 1.0 | 1.1 |
| C/C _⊙ ^d | 17.8 | 13.5 | 30 |
| N/N _⊙ ^d | 230 | 214 | 235 |
| O/O _⊙ ^d | 12.8 | 9.8 | 15.5 |
| χ^2 | 11 | 16 | 22 |

^a Filling factor, α and β allowed to vary.

^b Filling factor set at 1. α and β set to 0.

^c Uncertainties are comparable with those in Table 2.

^d Log of solar number abundances relative to hydrogen He:-1.0

C: -3.45 N:-4.03 O: -3.13 (Grevesse & Noel 1993).

Figure 1. H β line flux as a function of time after outburst. Squares are from Saizar et al. (1991), triangles are from Kenyon & Wade (1986) and the diamond is from Andreä et al. (1991). The dotted line represents equation 1.**Figure 2.** Top plot: Line fluxes of the observations and errorbars (triangles) and the best model (squares). Bottom plot: The χ^2 contribution of each line**Figure 3.** Elemental abundances of S91 (squares), A94 (diamonds), this paper (connected pluses) and Grevesse & Noel (1993) solar values (circles) for PW Vul 1984. We have slightly offset the elemental abundances of S91 and A94 to improve readability.**Figure 4.** Top two plots: Electron number density and electron temperature as a function of radius in the best fit July model. Bottom five plots: The normalized ion concentrations for H, He, C, N and O as a function of radius in the best fit July model.